PB87-115770

Movement of Selected Organic Liquids into Dry Soils

North Carolina State Univ. at Raleigh

Prepared for

Robert S. Kerr Environmental Research Lab.
Ada, OK

1986

U.S. Department of Commerce
National Technical Information Service
NTIS

PB87-115770

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA/600/J-86/152		

4. TITLE AND SUBTITLE
MOVEMENT OF SELECTED ORGANIC LIQUIDS INTO DRY SOILS
(Journal Version)

5. REPORT DATE
1986

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
A. Amoozegar[1], A. W. Warrick[2] and W. H. Fuller[2]

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
[1]North Carolina State University
Raleigh, NC 27659

[2]University of Arizona
Tucson, AZ 85721

10. PROGRAM ELEMENT NO.

11. CONTRACT/GRANT NO.
CR-810268

12. SPONSORING AGENCY NAME AND ADDRESS
Robert S. Kerr Environmental Research Lab. - Ada, OK
Office of Research and Development
U.S. Environmental Protection Agency
Ada, Oklahoma 74820

13. TYPE OF REPORT AND PERIOD COVERED

14. SPONSORING AGENCY CODE
EPA/600/15

15. SUPPLEMENTARY NOTES
Published in HAZARDOUS WASTE & HAZARDOUS MATERIALS, Vol. 3, No. 1, pp. 29-41, Spring 1986.

16. ABSTRACT
The movement of six organic liquids (toluene, xylene, kerosene, acetone, isopropyl alcohol and ethylene glycol) and water through five soils (Davidson, Ava, Canelo, Anthony and Mohave) was evaluated by measuring the rate of advance of the wetting front. Air dry soils were packed in glass columns of 2.1 cm inside diameter and 30-40 cm length. Pure liquids were added to one end of the column under a 0 to -1 cm of head using a constant head device. The position of the wetting front and the amount of liquids entering the soil column were measured simultaneously and were regressed against time using a power relationship (i.e. $x = at^b$ and $q = ct^d$). The rate of advancement of xylene was generally the fastest whereas ethylene glycol was the slowest. Of the soils considered, flow was fastest in the Mohave loam followed by Anthony (sandy loam). The experimental results were tested against theoretical predictions that the rate advance be proportional to the square root of time. Generally, the rate of advance of the pure organic liquid into dry soils can be related to the rate of advance of water and the saturated hydraulic conductivity values.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
RELEASE TO THE PUBLIC.	Unclassified.	14
	20. SECURITY CLASS (This page) Unclassified.	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS ED REPRODUCED BY

U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL
INFORMATION SERVICE
SPRINGFIELD, VA. 22161

HAZARDOUS WASTE & HAZARDOUS MATERIALS
Volume 3, Number 1, 1986
Mary Ann Liebert, Inc., Publishers
pp. 29–41

EPA/600/J-86/152
JOURNAL ARTICLE

Movement of Selected Organic Liquids into Dry Soils

A. AMOOZEGAR

North Carolina State University
Raleigh, NC 27650

A. W. WARRICK and W. H. FULLER

The University of Arizona
Tucson, AZ 85721

ABSTRACT

The movement of six organic liquids (toluene, xylene, kerosene, acetone, isopropyl alcohol and ethylene glycol) and water through five soils (Davidson, Ava, Canelo, Anthony and Mohave) was evaluated by measuring the rate of advance of the wetting front. Air dry soils were packed in glass columns of 2.1 cm inside diameter and 30–40 cm length. Pure liquids were added to one end of the column under a 0 to -1 cm of head using a constant head device. The position of the wetting front and the amount of liquids entering the soil column were measured simultaneously and were regressed against time using a power relationship (i.e. $x = at^b$ and $q = ct^d$). The rate of advancement of xylene was generally the fastest whereas ethylene glycol was the slowest. Of the soils considered, flow was fastest in the Mohave loam followed by Anthony (sandy loam). The experimental results were tested against theoretical predictions that the rate advance be proportional to the square root of time. Generally, the rate of advance of the pure organic liquid into dry soils can be related to the rate of advance of water and the saturated hydraulic conductivity values.

INTRODUCTION

Potentially hazardous organic liquids are in use throughout the modern world. Even with carefully designed storage and disposal facilities, accidental spills and leaks can occur. As liquids, these organic compounds can move through the soil and underlying materials to threaten the ground water (see for example Duffy et al., [1]). Once the ground water is contaminated, purification becomes difficult to say the least. Depending on the miscibility of the organic liquids with water, they may move through the soil as a solute or as a separate phase. For miscible fluids (i.e., those that mix easily with water) the relative concentration of the liquid may vary from 0 to 1. As for an immiscible liquid (e.g. xylene), solubility depends on its chemical nature. There are many instances where a pure organic liquid can enter the soil system and travel through the porous media before contacting free water. Under these conditions, it is necessary to be able to predict the movement of the liquid in the absence

NTIS is authorized to reproduce and sell this report. Permission for further reproduction must be obtained from the copyright owner.

of water although most systems will include a water component. Unfortunately, our understanding of the behavior of organic liquids in porous media and effects on the soil materials is severely limited. Relatively few studies have addressed the problem of the flow of these liquids through soils from the standpoint of their pollution potential.

Brown and Anderson [2] presented a review concerning the effects of organic chemicals on the permeability of clay liners used in land disposal sites. Anderson and Brown [3] and more recently Brown and Thomas [4] reported the effects of a number of organic liquids such as xylene, heptane, acetone, ethylene glycol, gasoline, kerosene, motor oil, and diesel fuel on the conductivity of clay materials used as liners. In most cases the conductivity values for the organic liquids were significantly greater or equal to that of water.

Schramm et al. [5] measured the saturated conductivity and calculated the intrinsic permeability of eight soils for xylene, kerosene, isopropyl alcohol, ethylene glycol, and water. In general, the saturated conductivity was highest for xylene and lowest for ethylene glycol. Except for sand, the intrinsic permeability of the soils calculated from water conductivity was lower than the calculated intrinsic permeability for the organic liquids. This suggests possible effects of the perfusing organic fluids on the soil structure. Frankenberger and Troeh [6] also measured the saturated conductivity, using two soils with methanol, n-propanol and water. The conductivity decreased to a steady state after 1500 hours of continuous leaching, with water having the highest value and methanol the lowest. They attributed the lower conductivity values of the soils to microbial activity. The saturated conductivity of two Arizona soils for water and trichloroethelene (TCE) and TCE saturated water was determined by Bolton [7]. His results indicated a much greater conductivity value for pure TCE compared to water and TCE saturated water. He also reported that for both soils the calculated intrinsic permeability for pure TCE was higher than for the water or TCE saturated water.

None of the above studies evaluated the infiltration of the organic liquids into a dry soil. In fact, few studies reported in the literature have addressed the infiltration and the unsaturated flow of organics through porous materials. Laughlin and Davis [8] measured the rate of rise of a light lubricating oil in various wicking materials. The capillary rise of water, toluene and some other organic liquids such as ethanol in glass beads or sand were determined by van Brakel and Heerjets [9]. Nielsen et al. [10] evaluated the horizontal movement of water and a light oil fraction (Soltrol-190) in two soils and a sandstone.

The objective of this study is to test whether movement of organic solvents into dry soil follows the generally accepted forms for water--i.e. is the rate of advance and the amount entering proportional to the square root of time when gravity is not a factor? Furthermore, an objective is to develop and test theoretical relationships useful for predicting movement of an organic liquid into dry soils based on measurements of water and limited data on the organic.

THEORY

Mathematical models to describe the movement of organic liquids through soils are limited, although there are several to describe water movement. The most rigorous models are based on Richards' equation for flow in unsaturated systems. For horizontal sorption (i.e. neglecting gravity) into an initially dry soil, a relationship between position x, water content θ and time t is

$$x = \lambda(\theta)t^{0.5} \qquad (1)$$

subject only to the following assumptions:

(1) Darcy's law is valid.
(2) Soil water diffusivity is a unique function of θ.
(3) The boundary and initial conditions are consistent with Eq. 1

Furthermore, a direct consequence is that the cumulative intake q is

$$q = St^{0.5} \qquad (2)$$

with the sorptivity S given by

$$S = \int_{\theta_i}^{\theta_f} \lambda(\theta)\, d\theta \qquad (3)$$

and θ_i and θ_f the initial and final water contents.

It follows from Eq. 1 that the "wetting front" position x_f (defined as where the water content is θ_f) is proportional to the square root of time, i.e.

$$x_f = at^{0.5} \qquad (4)$$

with $a = \lambda(\theta_f)$ which is constant. This is consistent with less rigorous analyses similar to the Green and Ampt approach (cf. Kirkham and Powers, 1972, esp. p. 237) [11] which results in

$$a = (-2K\Delta h/f)^{0.5} \qquad (5)$$

with K a single "wet" conductivity value, Δh the head difference between the wetting front and inlet and f the water-filled porosity. (The value of Δh will be negative.) By conservation of mass, a value corresponding to S is given by

$$c = (-2fK\Delta h)^{0.5} \qquad (6)$$

When gravity is included, the relationship between position, time and water content (θ) is more complex. Philip [12] developed his well-known "semi-analytical" solution for infiltration

$$x = \lambda t^{0.5} + \chi t + \Psi t^{1.5} + \ldots \qquad (7)$$

where λ, χ and Ψ are functions of water content and derivable from the basic soil properties. For large times, Eq. 7 is divergent and an alternative form is used. For small times it reduces to Eq. 1.

Assuming any liquid of interest infiltrates according to the square root of time as for water, we write

$$x_s = a_s t^{0.5} \qquad (8)$$
$$q_s = c_s t^{0.5} \qquad (9)$$

where the subscript "s" refers to the liquid (or solvent) of interest. By use of Eq. 4 and 5 for a "solvent" and "water", we may write the dimensionless quantities

$$a_s c_s/(K_s\, \Delta h_s) = a_w c_w/(K_w\, \Delta h_w)$$

or equivalently

$$a_s c_s/(a_w c_w) = (\Delta h_s/\Delta h_w)\,(K_s/K_w) \qquad (10)$$

If $\Delta h_s/\Delta h_w = \rho_s/\rho_w$, that is, the ratio of pressure heads (matric potentials) is approximately the density ratio, then

$$a_s c_s/(a_w c_w) = (\rho_s K_s/\rho_w K_w) \qquad (11)$$

This provides a possibility for predicting a_s (and/or c_s) based on data for water and the respective hydraulic conductivities.

Eq. 2 and 4 may be generalized as

$$x = at^b \qquad (12a)$$
$$q = ct^d \qquad (12b)$$

Laughlin and Davis [8] found "b" values of 0.41 to 0.5 appropriate for experiments on textile materials and paper wicking using oil.

MATERIALS AND METHODS

Five soils and seven liquids with contrasting characteristics were used for this study. Physical and chemical properties of the soils are presented in Table 1. The soils were air dried and passed through a 2 mm sieve. The six organic liquids and some of their properties are reported in Table 2. The seventh liquid was distilled water.

TABLE 1.

Some Characteristics of the Soils Used.

Series	Order	Clay	Silt	Soil Paste pH	Cation Exch. Capacity	Bulk* Density	Soil Surface Area	Predominant Clay Minerals
		-----%-----			cmol(+) kg^{-1}	Mg m^{-3}	m^2 kg^{-1}	
Davidson	Ultisol	52	23	6.4	9	1.41	151,300	Kaolinite
Ava	Alfisol	31	60	4.5	19	1.51	61,500	Vermiculite, kaolinite
Canelo	Alfisol	26	29	5.4	6	1.62	35,000	Kaolinite
Anthony	Entisol	15	14	7.8	10	1.79	49,800	Montmorillonite, mica
Mohave	Aridisol	11	37	7.3	10	1.69	38,300	Mica, kaolinite

* Average bulk density of the soil columns.

TABLE 2.

Properties of the Liquids Used (The source is Handbook of Chemistry and Physics, Weast [13], unless otherwise stated).

Liquids	Chemical Composition	η-Viscosity[a]	ρ-Density[a]	σ-Surface tension[a]	Polarity[d]	Dielectric Coefficient	Miscibility with water
		mPa s	Mg m^{-3}	mN s^{-2}	Debye		
Toluene	$C_6H_5CH_3$	0.59[b]	0.87	28.5	0.43	2.4	Immiscible
Xylene	$C_6H_4(CH_3)_2$	0.93[e]	0.87[b]	29.1[b]	0.29[b]	2.4	Immiscible
Kerosene[c]	C_{12} - C_{18} hydrocarbons	0.7-0.9[e]	0.82	30.7-31.2[e] (at 85°C)	(not available)	2.5	Immiscible
Acetone	CH_3COCH_3	0.42[e] (at 15°C)	0.79	23.7	2.86	20.7	Miscible
Isopropyl Alcohol	C_3H_7OH	2.86 (at 15°C)	0.79	21.7	1.63	18	Miscible
Ethylene Glycol	CH_2OHCH_2OH	19.9	1.11	47.7	2.31	37	Miscible
Water	H_2O	1.002	1.00	72.75	1.85	80	--

a. η, ρ and σ are at 20°C unless otherwise stated
b. Average
c. Data obtained from manufacturer
d. McClellan [14]
e. Brown and Thomas [4]

Glass tubes of 2.1 cm inside diameter and 30-40 cm long were packed with each soil at the bulk density listed in Table 1. To minimize layering, a funnel connected to a plastic tube was filled with soil and inserted into the glass column. Small quantities of the soil were released into the column at intervals and packed with a thin steel rod. The packing procedure was similar to the method used by Davidson et al. [15] except that, because the columns in our study were glass tubes, the soil was packed by tamping with a rod instead of shaking. The uniformity of the packing was checked visually and any column with layering was repacked.

The soil columns were oriented in either the horizontal or vertical direction. Each liquid was applied to one end of a soil column through a constant head device. The constant head devices were constructed using 50 ml buretts. Figure 1 shows the schematic diagram of the soil column and the constant head device for vertically upward, horizontal, and vertically downward infiltration. For the downward infiltration, the liquid head was maintained at about the top of the soil column (i.e. 0 to -1 cm head), for upward flow the head was at the lower part of the column, and for horizontal flow the head was at the middle of the column (see Figure 1). The position of the wetting front and time were recorded simultaneously beginning at the time of application (i.e. t = 0). In addition, the volume of the liquid entering the soil column was recorded at each measurement.

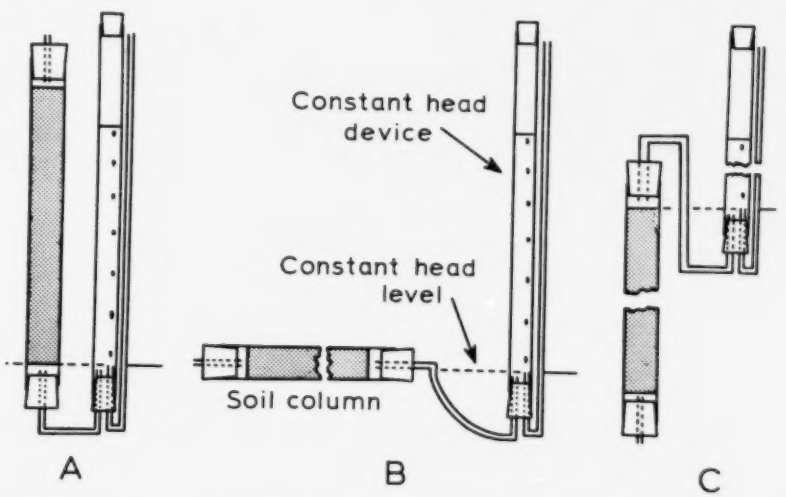

FIGURE 1. Schematic Diagram of the constant head device:
A. Vertical upward
B. Horizontal
C. Vertical downward

The rate of advance of toluene and acetone in a horizontal column of soil was determined for all five soils using five and three replications, respectively. The horizontal rate of advance of xylene, kerosene, isopropyl alcohol, ethylene glycol and water in Anthony s.l. was determined using three replications. In addition, the rate of advance of the wetting front of water, xylene, kerosene, isopropyl alcohol, and ethylene glycol through Ava, Davidson, Canelo, and Mohave soils was determined vertically upward, horizontally, and vertically downward using only one run for each of the 60 (5 x 4 x 3) combinations.

RESULTS AND DISCUSSION

The experimental data for horizontal infiltration of all seven liquids in Anthony s.l. were fitted to Eq. 12a and the mean and the standard deviation values of a and b are presented in Table 3. The correlation coefficient (r) for all cases was greater than 0.99 indicating a good linear relationship between log x and log t. The differences among the replications were negligible for most cases. The coefficient of variation for both a and b for xylene, kerosene, and ethylene glycol were between 1.8 and 3.8%. For water, acetone, isopropyl alcohol and toluene, the results were more variable with a maximum CV of 9.7% for the coefficient "a" for acetone and the highest CV of 6.3% for exponent "b" for isopropyl alcohol.

TABLE 3

The Mean Values and Standard Deviations for a, b, c and d for Horizontal Movement into Anthony s.l. (Units are consistent with length as cm, time as min.)

LIQUIDS

		Toluene	Xylene	Kerosene	Acetone	Isoprophyl Alcohol	Ethylene Glycol	Water
a	mean	3.05	2.58	2.16	2.91	1.41	0.892	2.04
	s	0.168	0.0797	0.0405	0.283	0.136	0.0342	0.109
	CV%	5.51	3.09	1.87	9.73	9.23	3.83	5.36
b	mean	0.483	0.501	0.500	0.426	0.473	0.408	0.464
	s	0.019	0.0119	0.0132	0.025	0.0300	0.0136	0.0151
	CV%	3.93	2.38	2.64	5.87	6.33	3.32	3.25
	95% C.I	±0.024	±0.030	±0.033	±0.062	±0.075	±0.034	±0.038
c	mean	2.51	2.65	2.05	2.43	1.45	0.808	1.61
d	mean	0.472	0.488	0.497	0.483	0.469	0.403	0.474
	95% C.I	±0.016	±0.073	±0.041	±0.102	±0.044	±0.043	±0.058

The amount of liquid infiltrating the soil column was also measured for each replication and regressed against time by the power relationship, Eq. 12b. Using our experimental data, c and d were determined and the resulting values are presented also in Table 3. Again, the correlation coefficients for all replications were greater than 0.99 which indicates a highly linear relationship between log q and log t during the experiment.

The distances to the wetting front vs. time for the horizontal infiltration of xylene, water and ethylene glycol in Anthony s.l. are presented in Figure 2. Note that both distance and time are expressed on a logarithmic scale. The graphs presented are obtained by using the average values of a and b in Eq. 12a. The results indicate that toluene and xylene moved the fastest in Anthony soil while ethylene glycol moved the slowest. This was also true for other soils. Ethylene glycol consistently advanced slowest while toluene and xylene advanced fastest. In most cases the order was: toluene = xylene > acetone > kerosene > water > isopropyl alcohol > ethylene glycol.

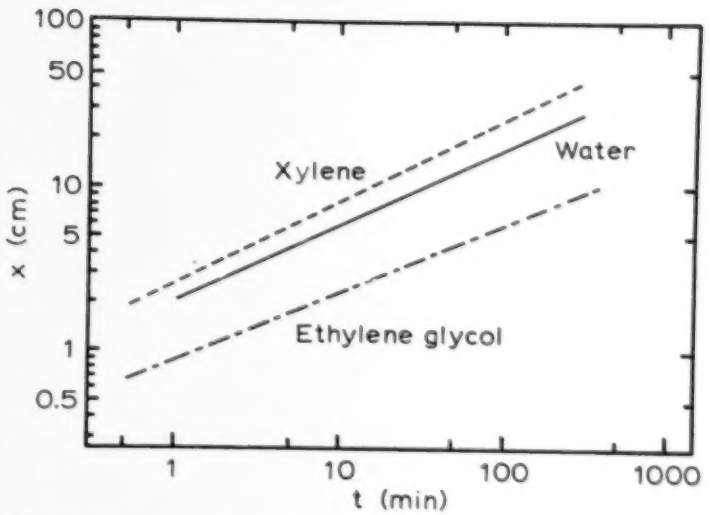

FIGURE 2. The Advancement of the Wetting Front for Horizontal Infiltration into Anthony s.l.

Figures 3 and 4 show the advancement of the wetting front through five soils for toluene and acetone, respectively. The graphs are obtained by using Eq. 4 and the average values of a and b as reported in Table 4. The fitted curves for all replications had r values greater than 0.99 indicating a consistent relationship between x and t^b.

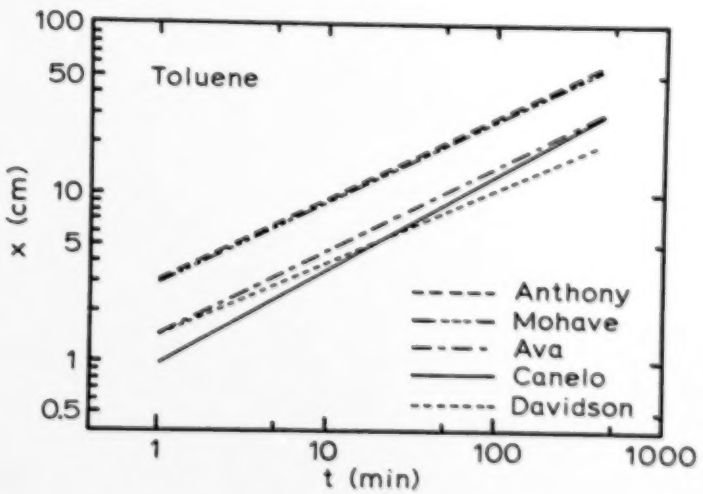

FIGURE 3. Wetting Front Distance vs. Time for Horizontal Infiltration of Toluene through Five Soils.

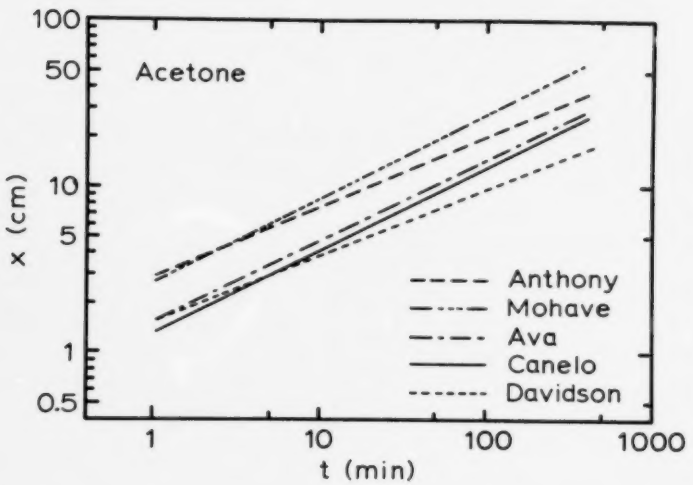

FIGURE 4. Wetting Front Distance vs. Time for Horizontal Infiltration of Acetone through Five Soils.

TABLE 4

The Mean and Standard Deviation for the Coefficients a and b of the Equation $x = at^b$ for Horizontal Infiltration of Toluene and Acetone into Five Soils

Liquid	Soil	a		b		
		Mean	s	Mean	s	95% C.I.
Toluene	Davidson	1.45	0.230	0.435	0.031	± 0.038
	Ava	1.46	0.208	0.496	0.032	± 0.053
	Canelo	0.969	0.145	0.560	0.021	± 0.026
	Anthony	3.05	0.168	0.483	0.019	± 0.024
	Mohave	2.91	0.286	0.485	0.040	± 0.050
Acetone	Davidson†	1.51	0.244	0.407	0.004	± 0.036
	Ava	1.57	0.131	0.490	0.022	± 0.055
	Canelo	1.33	0.045	0.498	0.002	± 0.005
	Anthony	2.91	0.283	0.426	0.025	± 0.062
	Mohave	2.69	0.230	0.510	0.005	± 0.012

† two replications

The results for the advancement of the wetting front of three liquids through Davidson in three directions are presented in Figure 5. Again, for most cases the relationship between the log x and log t for the duration of the experiment was linear. This was also true for Ava, Canelo, and Mohave soils. (Had the experiment been run for larger times probably a second term similar to Eq. 7 should be included.) The experimental data for each case was fitted to

Eq. 12a and 12b, and the values of a, b, c, and d estimated. The coefficient of determination, r^2, was generally larger than 0.98 with a few cases between 0.95 and 0.98.

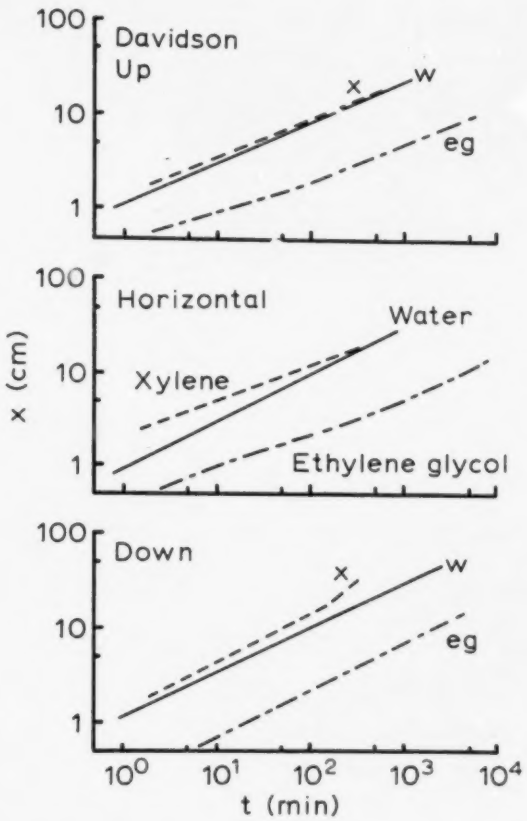

FIGURE 5. Advancement of the Wetting Front in Davidson for Vertical Upward, Horizontal, and Vertical Downward.

Confidence intervals at the 95% probability level for exponents b and d are reported in Tables 3 and 4. For most cases, b and d are not significantly different from 0.5. Therefore, the analyses presented for the horizontal infiltration of water using Eq. 4 are perhaps generally applicable to the organic liquids.

Comparing the soils, the organic liquids generally moved fastest in the Mohave soil, followed by Anthony. Our observations are consistent with the results of Schramm et al. [5] where Mohave had the highest saturated conductivity followed by Anthony and Canelo for five liquids used in their study. The advance of wetting fronts in our work for all liquids in Davidson, Ava, and Canelo soils were similar.

Considering the properties of the liquids, no apparent simple relationships exist between the rate of advance and the viscosity, density, and/or surface tension of the liquids--with the exception of the highly viscous ethylene glycol. For example, acetone has a viscosity of about 1/2 that of xylene and

toluene but generally advanced slower. The density of the liquids is: isopropyl alcohol < acetone < kerosene < toluene < xylene < water < ethylene glycol, which is not the order of advancement. The rate of movement of the liquids in these soils is not a simple function of the liquids' properties but apparently depends on a combination of the viscosity, density, polarity, and surface tension of the liquids as well as the clay, organic matter content, and a number of soil chemical characteristics.

The simple scaling relationship (Eq. 11) was tested and the results are presented in Figure 6 for 2 soils and 4 solvents. The ratio of measured saturated conductivity of solvents and water for the soils are from Schramm et al. [5]. For the limited number of soils and solvents, the results are close to the 1:1 (ρ_s/ρ_w = 1 for all liquids) line and hence judged to be in good agreement.

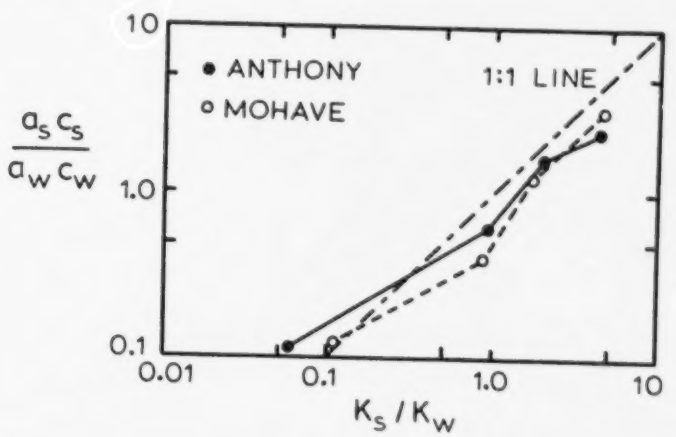

FIGURE 6. Dimensionless Plot of Proportionality Factors for Rate of Advance for Four Solvents in Two Soils. To agree totally the plots should fall on the 1:1 Line. (See esp. Eq. 10).

SUMMARY AND CONCLUSION

We measured the movement of six organic liquids and water through air-dried soils (less than 1% moisture) by determining the rate of advance of the wetting front horizontally, vertically upward and vertically downward. The position of the wetting front was regressed against time using a power curve (see Eq. 12a) with the exponent b varying between 0.35 and 0.61 for all cases. At a 95% probability level, the exponent b generally was not significantly different from 0.5. For completeness, however, the power curve was also used for water with the resulting exponent b ranging between 0.46 and 0.54 for all soils. The amount of liquid entering each soil was also regressed against time using a power curve. We have noted that the rate of advance of the wetting front and the amount of liquid infiltrating the soil is related to the saturated conductivity of the solvent as reported by Schramm et al. [5]. The consistency of the results indicates significant differences among the rates of movement of various solvents through different soils. For example, Figure 7 shows the relative mobility of xylene, water and ethylene glycol in the Mohave. The bars represent the distance traveled by the liquids in a soil column after 12 hours. Note that after 12 hours the ratio of horizontal mobility of xylene to ethylene glycol is 5:1 compared to 1.5:1 for xylene and water. The bars also indicate that in the

Mohave, xylene advances twice as fast as water in the downward direction. Similar analyses could be performed for other organic liquids or soils used in this investigation.

Table 5 presents the calculated distance advanced by the six organic liquids through five soils after 12 hours. Note that the rates of downward movement of xylene and kerosene are much larger than the corresponding rates for the other liquids. Xylene generally moved downward at a much faster rate than it advanced horizontally or vertically upward. As for the other liquids, only the downward movement rate through Mohave soil was considerably higher than the

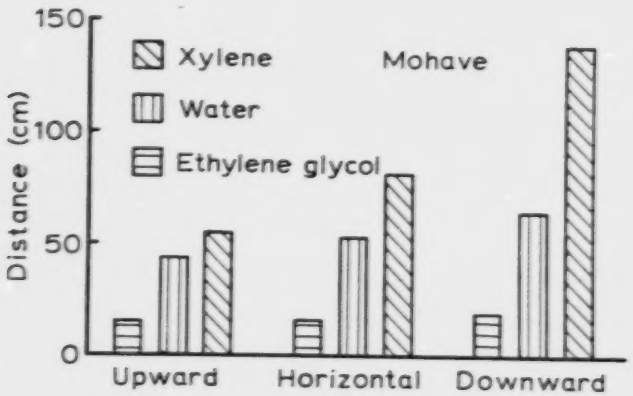

FIGURE 7. Calculated Distances Traveled by Three Liquids in the Mohave Soil after 12 Hours.

TABLE 5

The Calculated Distance Traveled by Solvents after 12 hours.

Soil	Direction	Solvents						
		Xylene	Kerosene	Isopropyl	Ethylene	Water	Acetone*	Toluene†
		cm						
Davidson	upward	20.5	24.8	12.2	4.6	23.1	-	-
	horizontal	24.0	29.5	13.6	4.54	25.9	22.0	25.4
	downward	42.6	33.9	17.4	5.7	23.6	-	-
Ava	upward	33.8	29.0	15.7	6.5	19.9	-	-
	horizontal	40.4	22.2	16.0	6.4	24.7	39.5	38.2
	downward	44.5	24.5	17.3	6.2	24.1	-	-
Canelo	upward	35.0	25.3	13.7	4.2	11.4	-	-
	horizontal	33.1	20.9	14.7	4.3	16.2	35.2	38.6
	downward	63.7	24.8	20.7	5.9	14.2	-	-
Mohave	upward	54.6	40.5	21.7	14.5	42.9	-	-
	horizontal	81.9	65.9	34.3	16.3	53.6	77.1	70.8
	downward	138.1	102.3	45.2	27.4	64.2	-	-
Anthony*	horizontal	69.5	58.1	31.7	13.1	43.2	48.0	73.2

* average of 3 replications
† average of 5 replications

rates in other directions. It must be noted that the calculated distances presented in Table 5 are based on one-dimensional results. Actual profile resulting from the leakage of an underground facility or an accidental spill at the

surface of a similar soil profile should lag behind the distances presented here because the flow would diverge radially as it moved down. However, we expect the relative positions of the front for the various solvents be the same. In the absence of a more comprehensive evaluation of the movement of various organic solvents through soils, the results presented in the above table (or similar tables or charts) may be used as a first approximation to estimate the rate of movement of pure solvents in the soil.

No simple relationship exists between the rate of advance and the viscosity, density, polarity, surface tension or other liquid properties of the solvents. However, a scaling relationship (Eq. 11) based on both water and organic liquid advancing with the square root of time was reasonably well satisfied. This may allow the prediction of the rate of advance of an organic liquid based on only its saturated permeability value and that of water for the same soil. Lack of information regarding the behavior of the organic chemicals and their effects on the soil structure underscores the great need for more research in this area.

DISCLAIMER

Although the research described in this article has been funded wholly or in part by the United States Environmental Protection Agency under assistance agreement CR-810268 to The University of Arizona, it has not been subjected to the Agency's peer and administrative review and therefore may not necessarily reflect the views of the Agency and no official endorsement should be inferred.

ACKNOWLEDGEMENT

Arizona Agric. Exper. Stat. Paper No. 3632. Support was in part from U.S. EPA CR-810268.

REFERENCES

1. Duffy, W. J., R. Moose, and J. S. Tomalavage. 1980. Contamination of Ground Water Supplies by Trichloroethylene - Three Case Histories. University of Wisconsin Municipal Industrial Waste Res. Practice Conf. Proc. Sept 10-12 pp. 187-200.

2. Brown, K. W., and D. Anderson. 1980. Effects of Organic Chemicals on Clay Liner Permeability. In D. W. Schultz (Ed.), Disposal of Hazardous Wastes. Proc. Sixth Ann. Res. Symp., Chicago, Illinois, 17-20 March 1980. Mun. Environ. Res. Lab, ORD, U.S. Environ. Protec. Agency, Cincinnati, Ohio.

3. Anderson, D., and K. W. Brown. 1981. Organic Leachate Effects on the Permeability of Clay Liners. In D. W. Schultz (Ed.), Land Disposal: Hazardous Wastes. Proc. Seventh Ann. Res. Symp., Philadelphia, Pennsylvania, 16-18 March 1981. Mun. Environ. Res. Lab, ORD U.S. Environ. Protec. Agency, Cincinnati, Ohio.

4. Brown, K. W. and J. C. Thomas. 1984. Conductivity of Three Commerically Available Clays to Petroleum Products and Organic Solvents. Hazardous Wastes 1:545-553.

5. Schramm, M., A. W. Warrick, and W. H. Fuller. 1985. Permeability of Soils to Four Organic Solvents and Water. Hazardous Waste. (This issue).

6. Frankenberger, W. T., Jr., and F. R. Troeh. 1982. Bacterial Utilization of Simple Alcohols and Their Influence on Saturated Hydraulic Conductivity. Soil Sci. Soc. Am. J. 46:535-538.

7. Bolton, M. W. 1984. Movement of Trichloroethylene Solution through Soils. M. S. Thesis, The Univ. of Arizona, Tucson. 55 pp.

8. Laughlin, R. D., and J. E. Davies. 1961. Some Aspects of Capillary Absorption in Fiberous Textile Wicking. Textile Research J. 31:904-910.

9. van Brakel, J., and P. M. Heertjes. 1977. Capillary Rise in Porous Media. Part I: A Problem. Power Technology 16:75-81.

10. Nielsen, D. R., J. W. Biggar, and J. M. Davidson. 1962. Experimental Consideration of Diffusion Analysis in Unsaturated Flow Problems. Soil Sci. Soc. Am. Proc. 26:107-111.

11. Kirkham, D. and W. L. Powers. 1972. Advanced Soil Physics. Wiley-Interscience. 534 p.

12. Philip, J. R. 1969. Theory of Infiltration. Advan. Hydro. Sci. 5:215-305.

13. Weast, R.D. 1974. Handbook of Chemistry and Physics. CRC Press, Inc., Boca Raton, FL.

14. McClellan, A. L. 1974. Tables of Experimental Dipole Moment. Vol. I. Rahara, El Cerrito, Calif.

15. Davidson, J. M., D. R. Nielsen, and J. W. Biggar. 1963. The Measurement and Description of Water Flow through Columbia Silt Loam and Hesperia Sandy Loam. Hilgardia 34(15):601-617.

Address reprint requests to:
A. Amoozegar
The University of Arizona
Tucson, AZ 85721

NOTICE

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

This article documents research that was conducted under the auspices of the U.S. Environmental Protection Agency (USEPA). As an arm of the government, the USEPA has a paid up, non-exclusive, irrevocable, worldwide license to reproduce, prepare derivative works, and distribute to the public all of the material contained herein, and to grant others acting on its behalf the right to do so. The USEPA grants to the National Technical Information Service, Department of Commerce, the right to act as its agent in the distribution of this material.